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Critical Boundary of Cascaded Quadratic Soliton Compression in PPLN

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Abstract: Cascaded quadratic soliton compression in PPLN is investigated and a general critical soliton number is found as the compression boundary. An optimal-parameter diagram for compression at 1550 nm is presented.
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1. Introduction

Soliton pulse compression based on cascaded quadratic nonlinearity is attractive because few-cycle near-IR pulses can be formed in short nonlinear crystals. The basic principle is that a self-defocusing cascading nonlinearity $n_{2,casc} \propto d_{eff}^2 / \Delta k$ counterbalances the native Kerr self-focusing nonlinearity $n_{2,Kerr}$ and through spectral broadening from self-phase modulation (SPM) a temporal soliton can form with normal dispersion that compresses the pulse in the initial soliton formation stage.

A systematical study on how the cascaded quadratic nonlinearity works in pulse compression in bulk β-barium borate (BBO) has already been reported [1-3]. An effective soliton number $N_{eff} \propto \left(n_{2,casc} + n_{2,Kerr}\right)$ was introduced to represent the counterbalance between the cascaded quadratic nonlinearity and the native self-focusing cubic nonlinearity. A successful pulse compression is supported by a N_{eff} larger than a critical value, which is unity for low intensities but increases for higher intensities due to cross-phase modulation (XPM) contributions to the nonlinear phase shift [4]. In this paper, we will further investigate cascaded quadratic soliton compression in a lithium niobate (LN) nonlinear crystal where the phase mismatch is controlled with quasi phase matching (QPM) structure. Using QPM is attractive as it exploits the largest quadratic nonlinearity d_{eff}, while with QPM a reduction on the phase mismatch Δk will help increasing the cascaded quadratic nonlinearity. Moreover, we find a general critical value of N_{eff} for periodically poled LN (PPLN).

2. Compression window for PPLN

We use PPLN as it is the most common material with QPM structure. In a Type-0 phase-matching configuration, the 2nd order nonlinearity mainly stems from the large d_{33} tensor component. The cost of using QPM is an extra pre-factor $2/\pi$ due to the 1st order QPM structure, i.e. $d_{eff} = (2/\pi)\cdot d_{33}$. Besides, The QPM changes the phase mismatch to an effective phase mismatch, $\Delta k_{eff} = \Delta k - 2\pi/\Lambda$. In past studies QPM cascading was used to generate the largest possible cascaded nonlinearity by choosing $\Delta k_{eff} \cdot L = \pi$. However, this is not optimal for ultrafast cascading: Firstly, Δk_{eff} should remain large to ensure a Kerr-like cascading (where the nonlinear index change is linear in intensity $\Delta n \propto n_{2,casc} I$), but small enough to compensate for the Kerr nonlinearity. Secondly, if Δk_{eff} becomes too small, the cascading becomes nonstationary (resonant) and for ultrafast compression a stationary (non-resonant) nonlinearity is required. The Δk_{eff} operation regime where this is possible is usually called compression window [2].

3. Results and discussion

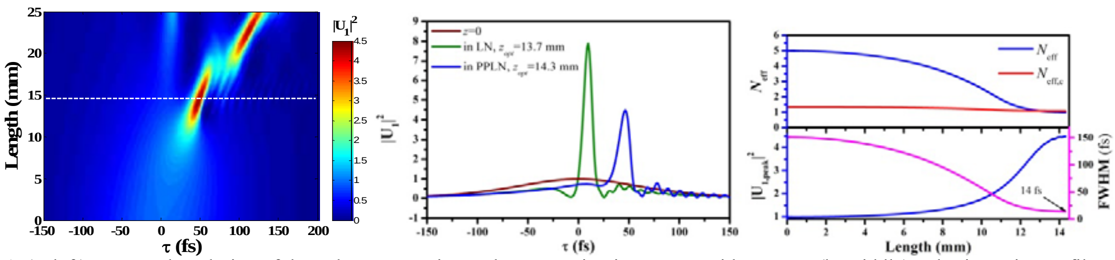

Fig. 1. (a, left) Temporal evolution of the pulse propagation and compression in a PPLN with $N_{eff} = 5$, (b, middle) pulse intensity profile at the best compressed length z = 14.3 mm, (c, right) the dynamics of soliton number as well as the critical soliton number during the compression process.

We investigate the pulse compression in PPLN at wavelength 1550 nm. The phase mismatch of bulk LN at this wavelength is Δk = 319.5 mm^{-1}. In PPLN with a poling period of 33 μm, the effective phase mismatch is Δk_{eff} = 129.5 mm^{-1}. The stationary threshold is Δk_{sr} = 113.1 mm^{-1}. The reduction of the phase mismatch happens to compensate the loss on d_{33} and therefore the value of self-defocusing cascading nonlinearity is as same as what in bulk LN, $n_{2,casc} = -2.8\times10^{-15}$ cm^2/W, which in quantity is higher than the native Kerr self-focusing nonlinearity $n_{2,Kerr} = 1.7\times10^{-15}$ cm^2/W. Hence, Δk_{eff} is exactly in the compression window. Using a pulse with 150 fs FWHM and 75 GW/cm^2 peak intensity, $N_{\rm eff} = 5$ is achieved and simulation shows that few-cycle pulse is generated after a 14.3 mm propagation, see Fig. 1. The compressed pulse has a FWHM of 14 fs (no more than 3 cycles) and the peak intensity is increased over 4 times. Compared with the soliton pulse generated in bulk LN (10.1 fs and 8 times in intensity), the soliton pulse generated in PPLN is a little degraded with lower peak intensity and longer pulse duration. This degradation is mainly due to the high level of GVM which sets a high stationary threshold. Then the QPM-induced reduction of phase mismatch forces the compression to be close to the stationary boundary and therefore to be less clean. In the contrary, if GVM is reduced, Δk_{eff} will have enough space of reduction. Then a higher level of $n_{2,casc}$ in PPLN than that in bulk LN is expectable and the compression will be upgraded.

Another way to supply the cascading nonlinearity is to increase the energy fluence, which is defined as $\Phi = 2T_0I_0$. Since the high energy fluence will evoke a significant Kerr XPM, which adds to the Kerr SPM and thereby dynamically increases the overall competing Kerr self-focusing nonlinearity, the compression condition $N_{eff} > 1$ will be no longer enough. A critical effective soliton number $N_{eff,\,c}$ must be found and the pulse compression is therefore expectable with $N_{eff} > N_{eff,\,c}$. Figure 2 shows some simulation results under a wide span of energy fluence, from which a boundary of N_{eff} is found as $N_{eff,\,c}$.

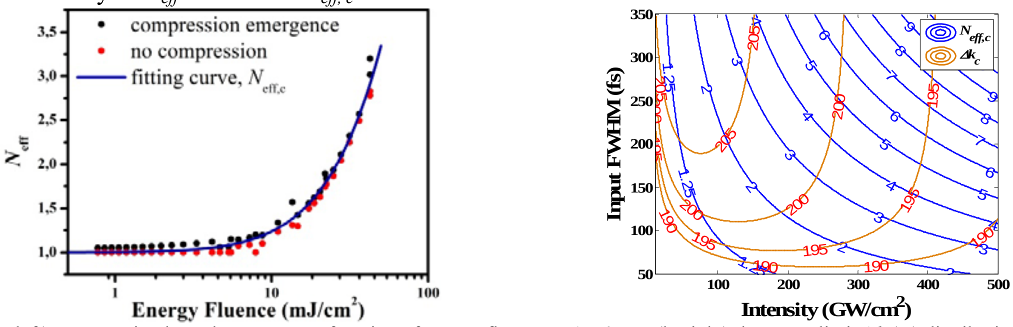

Fig. 2. (a, left) compression boundary $N_{\rm eff,c}$ as a function of energy fluence at 1550nm, (b, right) the upper limit $\Delta k_c(\Phi)$ distribution as a function of the input FWHM and peak intensity of the launched pulse.

The revision of the compression condition is equivalent to a revision on the upper limit of the phase mismatch, called critical phase mismatch $\Delta k_c(\Phi)$. Hence, a more precise compression window can be concluded, i.e. $\Delta k_{sr} < \Delta k_{eff} < \Delta k_c(\Phi)$. With a wide span of the parameters of a launched pulse, the distribution of Δk_c and $N_{eff,\,c}$ is shown in Fig. 2(b), which is believed helpful in the design of the QPM structure.

Moreover, we also give the dynamics of N_{eff} together with $N_{eff,\,c}$ during the formation of the soliton pulse, shown in Fig. 1(c). It is obvious that the difference $N_{eff} - N_{eff,\,c}$ at the starting point gives the capacity of the pulse compression, and when the best compressed pulse is formed, this capacity is almost exhausted.

4. Conclusion

We numerically investigated cascaded quadratic soliton compression in PPLN. With high energy fluence used to supply a cascaded nonlinearity, a critical soliton number becomes significant. Hence, a general critical soliton number $N_{eff,\,c}$ is found through a careful study. Moreover, the soliton number dynamics are shown as the capacity of compression and a best compression corresponds to an exhausted capacity. Finally, we presented a phase-space plot where the critical parameters for optimal pulse compression at 1550nm in PPLN can extracted.

5. Reference

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